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The Acoustic Repertoire of Odontecetes as a Basis for Developing Automatic Detectors and Classifiers

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DRDC Atlantic has an ongoing research program that requires the transmission of acoustic energy in an undersea environment. Though the transmissions are generally at a relatively low level, every effort must be made to mitigate the potential for impact on marine life. Future impact mitigation measures may include the development detection/classification capabilities for marine mammal vocalizations. The ocean environment tends to be noisy, so that the detection of noise itself is inadequate for alerting researchers of the presence of marine mammals. The "noise" must be classified as to its origin. e.g. has it been generated by a marine mammal. The objective of this study was to further DRDC's understanding of whale vocalizations with the aim of developing automatic acoustic whale detectors and identifiers.

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Abstract

DRDC Atlantic has an ongoing research program that requires the transmission of acoustic energy in an undersea environment. Though the transmissions are generally at a relatively low level, every effort must be made to mitigate the potential for impact on marine life. Future impact mitigation measures may include the development detection/classification capabilities for marine mammal vocalizations. The ocean environment tends to be noisy, so that the detection of noise itself is inadequate for alerting researchers of the presence of marine mammals. The “noise” must be classified as to its origin. e.g. has it been generated by a marine mammal. The objective of this study was to further DRDC's understanding of whale vocalizations with the aim of developing automatic acoustic whale detectors and identifiers.

Résumé

Un des programmes de recherche de RDDC Atlantique implique l’émission d’énergie acoustique dans l’environnement sous-marin. Bien que les émissions soient généralement peu intenses, il est très important d’atténuer la possibilité d’impact sur la vie marine. Parmi les mesures d’atténuation possibles, on compte la mise au point de moyens de détection et d’identification des « chants » des mammifères marins. L’environnement sous-marin est souvent bruyant, ainsi les chercheurs ne peuvent se fier à la simple détection de bruit pour déduire la présence de mammifères marins. On doit classer — identifier — le « bruit » en fonction de son origine : provient-il d’un mammifère marin? Cette étude a comme objectif d’améliorer les connaissances de RDDC relatives aux chants des baleines, afin de mettre au point des détecteurs et des identificateurs automatiques de baleines.

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Executive summary

Background

DRDC Atlantic has an ongoing research program that requires the transmission of acoustic energy in an undersea environment. Though the transmissions are generally at a relatively low level, every effort must be made to mitigate the potential for impact on marine life.

Recent increased awareness regarding the potential for adverse impact on marine fauna from anthropegenic noise, have resulted in further research being undertaken to study the impact mechanisms and possible mitigation measures. Future impact mitigation measures may include the development detection and classification capabilities for marine mammal vocalizations. The ocean environment tends to be noisy, so that the detection of noise itself is inadequate for alerting researchers of the presence of marine mammals. The “noise” must be classified as to its origin. e.g. has it been generated by a marine mammal. The objective of this study was to further DRDC's understanding of whale vocalizations with the aim of developing automatic acoustic whale detectors and identifiers.

Results

This study considered the sound produced by 28 Odontocete (toothed whales) species. Through a literature survey, the characterization of many of the species sound production has been included. As interesting as the wealth of knowledge regarding some species such as Sperm Whales is the lack of knowledge for almost half of the stud, including many beaked whale species.

Significance

Many researchers perceive that beaked whales (Ziphioidea) may be at most risk to the potential impact of sonar transmissions. Much of the world-wide effort investigating the impact of Naval sonars on marine mammals is focussing on Beaked whales. Within that, large portions of the resources are being focused on Cuvier’s beaked whales. The lack of known sounds being produced by such animals causes a significant problem in implementing detection and classification algorithms. Efforts, such as those undertaken at the NATO Undersea Research Centre, to characterize “sounds,” behaviour, and habitat are critical to developing feasible measures to mitigate the impact of anthropogenic noise. Not surprisingly, detection and classification mitigation measures are likely to work with some species, but not with all.

Future Plans

This study, undertook to look at 28 of the 80 known Cetacea. Obvious extensions are to increase the survey set to include other species, and to implement detection and classification algorithms directed identifying known species.

ERBE, C. 2004. The Acoustic Repertoire of Odontocetes as a Basis for Developing Automatic Detectors and Classifiers. DRDC Atlantic CR 2004-071. Defence R&D Canada – Atlantic

Sommaire

Contexte

Un des programmes de recherche de RDDC Atlantique implique l'émission d'énergie acoustique dans l'environnement sous-marin. Bien que les émissions soient généralement peu intenses, il est très important d'atténuer la possibilité d'impact sur la vie marine.

La prise de conscience récente de la possibilité d'effets négatifs sur la faune marine des bruits d'origine humaine a entraîné de nouvelles recherches pour en étudier les effets et les mesures possibles d'atténuation. Parmi les mesures d'atténuation possibles, on compte la mise au point de moyens de détection et d'identification des « chants » des mammifères marins. L'environnement sous-marin est souvent bruyant, ainsi les chercheurs ne peuvent se fier à la simple détection de bruit pour déduire la présence de mammifères marins. On doit classer — identifier — le « bruit » en fonction de son origine : provient-il d'un mammifère marin? Cette étude a comme objectif d'améliorer les connaissances de RDDC relatives aux chants des baleines, afin de mettre au point des détecteurs et des identificateurs automatiques de baleines.

Résultats

Au cours de l'étude, nous avons considéré les sons émis par 28 odontocètes (baleines à dents). Une recension des écrits nous a permis de caractériser l'émission de chants par plusieurs espèces. Il est intéressant de noter l'abondance d'informations relatives à certaines espèces, comme le cachalot, et l'absence de connaissance pour la moitié de l'ensemble, notamment de nombreuses baleines à bec.

Importance des résultats

Plusieurs chercheurs croient que les cétacés les plus sensibles à l'effet possible des émissions sonar sont les baleines à bec (ziphiidés). Ainsi, au palier mondial, une bonne partie des travaux sur les effets des sonars militaires est consacrée aux baleines à bec, et une forte proportion des ressources est destinée à la baleine à bec de Cuvier. On ne connaît aucun des sons émis par ces animaux, ce qui constitue un problème important pour la mise en service d'algorithmes de détection et d'identification. Les travaux entrepris pour caractériser leurs sons, leur comportement et leur habitat, comme ceux effectués par le Centre de recherche sous-marine de l'OTAN sont essentiels pour la mise au point de mesures pratiques d'atténuation des bruits d'origine humaine. Comme on peut s'y attendre, des mesures de détection et d'identification fonctionneront probablement avec certaines espèces et pas du tout avec d'autres.

Futurs travaux

Cette étude a porté sur 28 des 80 espèces connues de cétacés. Des développements évidents issus de ce travail sont l'ajout d'autres espèces à l'ensemble étudié et la mise en œuvre des algorithmes de détection et d'identification des espèces connues.

ERBE, C. 2004. *The Acoustic Repertoire of Odontocetes as a Basis for Developing Automatic Detectors and Classifiers.* (Répertoire acoustique des odontocètes comme fondement de la mise au point de détecteurs et d'identificateurs automatiques) RDDC Atlantique CR 2004-071. R&D pour la défense Canada – Atlantique

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Objective

The objective of this study was to further DRDC's understanding of whale vocalizations with the aim of developing automatic acoustic whale detectors and identifiers. These could ultimately be used to mitigate potential acoustic impact by DRDC's marine activities.

1. Introduction

Since the beginning of industrialization, man-made noise in the marine environment has steadily increased. Underwater noise has reached levels where it can seriously harm marine organisms and impact their survival. Over the last two decades, public interest in the well-being of whales and dolphins has grown to unprecedented strength, posing pressure on the marine industry, military and ocean research. Recent circumstantial evidence has raised concerns over the potential impact of sonars on toothed whales, in particular beaked whales. Significant effort has been undertaken to look at methods of mitigating the potential impact on these whales. As a first step, the presence of an animal at the location of human activity needs to be known. A favourable method which does not cause any impact on marine mammals is passive acoustic detection, classification and localization. Once it is known what species of animal is present at what distance from the human activity, then various mitigation methods could be investigated. Merely to give the reader an idea, such mitigation methods may include an alteration to the sound emission protocol and procedure, temporarily shutting down, changing the exposure time or duty cycle, reducing output levels, ramping up the sound source level or others.

An intrinsic part of the effectiveness of passive acoustic detection is that the whale must produce a recognizable sound. All marine mammals emit sound for communication purposes. Odontocetes (toothed whales) further emit echolocation signals to detect, characterize and locate objects (e.g. prey or geographic features) under water. Marine mammals communicate during social interactions, while foraging, in conjunction with mating, competition and maternal behaviour, and during travel. They might transmit information about individual identification, reproductive status, habitat and territories, prey and predators. The information content of particular sounds remains largely elusive. The correlation of sound with behaviour is difficult even under captive circumstances and hardly known for animals in the wild.

For the purpose of developing passive acoustic detectors, the important first step is to characterize the acoustic repertoire of marine mammal species. This project gathered information on calls emitted by selected odontocetes. The focus was on sperm whales, porpoises and beaked whales. Beaked whales often seem to be more susceptible to acoustic impact than other odontocetes. Also, they are less studied than their dolphin relatives.

Data is presented in tabular format, sorted by species. For each species the repertoire was organized into typical call types, e.g. whistles, harmonic calls, clicks. For each call type, the main characteristics (bandwidth, dominant frequency, temporal pattern, and sound pressure level) were characterized. For each reference used, the area where the calls were observed was listed. This is important, because different populations of the same species might use different calls. In other words, recordings of the same species might differ from location to location. And very important, recordings made in aquaria tend to vary considerably from recordings made in the wild. Captive animals often develop different calls over time be it due to the fundamentally different reverberation in a tank environment compared to the open environment or be it due to different acoustic exposure and ambient noise.

2. Odontocete Species

Whales and dolphins make up the animal Order of Cetacea. Toothed whales fall into the Suborder Odontoceti, baleen whales fall into the Suborder Mysticeti. Each Suborder comprises various animal Families. The Suborder Odontoceti consists of the large Family of Delphinidae (dolphins), The Family of Monodontidae (the beluga and narwhal), the Superfamily of Platanistoidea (river dolphins and Franciscana dolphin) as well as the following Families which are studied in more detail in the current project:

2.1 Selected Species

Porpoises	**Phocoenidae**
Dall's Porpoise	Phocoenoides dalli
Spectacled Porpoise	Australophocaena dioptrica
Harbour Porpoise	Phocoena phocoena
Vaquita	Phocoena sinus
Burmeister's Porpoise	Phocoena spinipinnis
Finless Porpoise	Neophocaena phocaenoides
Sperm Whales	**Physeteroidea**
Sperm Whale	Physeter catodon / macrocephalus
Pygmy Sperm Whale	Kogia breviceps
Dwarf Sperm Whale	Kogia simus

Beaked Whales	Ziphioidea
Baird's Beaked Whale	Berardius bairdii
Arnoux's Beaked Whale	Berardius arnuxii
Northern Bottlenose Whale	Hyperoodon ampullatus
Southern Bottlenose Whale	Hyperoodon planifrons
Cuvier's Beaked Whale	Ziphius cavirostris
Shepherd's Beaked Whale	Tasmacetus shepherdi
Blainville's Beaked Whale	Mesoplodon densirostris
Sowerby's Beaked Whale	Mesoplodon bidens
Gervais' Beaked Whale	Mesoplodon europaeus
True's Beaked Whale	Mesoplodon mirus
Strap-toothed Beaked Whale	Mesoplodon layardii
Gray's Beaked Whale	Mesoplodon grayi
Andrew's Beaked Whale	Mesoplodon bowdoini
Longman's Beaked Whale	Mesoplodon pacificus
Hector's Beaked Whale	Mesoplodon hectori
Ginkgo-toothed Beaked Whale	Mesoplodon ginkgodens
Stejneger's Beaked Whale	Mesoplodon stejnegeri
Hubbs' Beaked Whale	Mesoplodon carlhubbsi
Pygmy Beaked Whale	Mesoplodon peruvianus

2.2 Call Types

The following sections list the characteristics of recorded calls by species. I have grouped the calls into the following types: Clicks are usually very brief and somewhat broadband signals, in the sense that the energy-versus-frequency plot would show a somewhat Gaussian distribution. Most clicks have one frequency band of maximum energy, some clicks have more than one. By contrast, I classified calls as harmonic calls if the energy-versus-frequency plot was made up of a series of distinct frequency peaks. Not all of these had to be necessarily harmonically related. These calls are usually longer in time duration. I used the frequency spectra and spectrograms provided in the particular article to classify the calls. The classification therefore depended on the actual time window and frequency band used by the corresponding authors. Spectrograms might look rather different if the analyzing windows are changed. Echolocation clicks are clicks that have been proven to be used for echolocation. Therefore some of the clicks might not be communication clicks but actually function in echolocation, however, the authors did not attempt to show the echolocation purpose at the time.

The respective authors often used a different nomenclature for the recorded signals. Classifications such as **FM** (frequency-modulated) calls or **AM** (amplitude modulated) calls were kept (e.g. Baird's and Arnoux's Beaked Whale). Many authors tried to group the calls into classes indicating what they sound like to the human ear. One finds at least two dozen such call types in the literature including grunts, moans, croaks, growls, bellows, squeals, clangs, gunshots, trumpets, chirrups, pips and so forth. I tried to avoid these descriptions, unless the scientific community widely accepted them, as in the case of sperm whale creaks.

2.3 Bandwidth

As bandwidth I used the total frequency band of the signal. In an energy-versus-frequency plot, this would be the range from the lowest frequency showing signal energy to the highest frequency; basically the two extremes where energy is detectable before the signal dissipates into noise. The actual bandwidth is the difference between the high cut-off frequency and the low cut-off frequency. In these cases I listed the bandwidth as high cut-off frequency minus low cut-off frequency, i.e. the higher frequency is listed first. An example would be the harbour porpoise clicks in section 3.3 that showed energy at frequencies from 20kHz down to 400Hz, with the maximum energy lying somewhere between 2 and 4kHz.

For Gaussian-shaped frequency spectra (e.g. in the case of clicks), the bandwidth is often defined as the width of the curve at the half-power points. These points are more clearly identifiable than the points at which the signal dissipates into noise. The corresponding bandwidth should correctly be called the 3dB-bandwidth. I have indicated this as, e.g., in section 4.1 for the pygmy sperm whale clicks with a bandwidth of 20kHz "@3dB". With this type of frequency spectrum, the frequency of maximum energy (the peak) lies in the centre of the spectral curve. The bandwidth is symmetrical about the frequency of maximum energy. Most authors therefore don't list the cut-off frequencies individually but give the bandwidth as the worked-out subtraction. The bandwidth would just be one number. However, due to the statistical nature of biological signals, there is usually a range of measured bandwidths. This range is listed as lower number first, higher number second. An example would be the Dall's porpoise clicks in section 3.1 with a dominant frequency between 125-135kHz and a bandwidth ranging from 5kHz to 10kHz.

2.4 Dominant Frequency

This one is straight-forward: It is the frequency of maximum sound energy.

2.5 Duration/Repetition

For single calls, I listed the duration of the signal. For clicks in a sequence, I used this column to describe the duration of individual clicks, the number of clicks per second (click rate), the total length of a sequence, the inter-click-interval (**ICI**), or whatever information the corresponding authors made available.

2.6 Source Level

This is the level of the signal referred to 1m distance from the source, listed in dB re 1 μPa. The corresponding authors would have either measured this directly in a captive environment where hydrophones could be placed in close proximity to the head of the animal. In the wild, the authors would have done some sound propagation modelling to relate the received signal level back to the level at the source.

Normally, source levels are related to the root-mean-square (rms) value of the corresponding time series. To indicate this, one would write a source level in dB_{rms}. In the case of very brief / pulsed signals, the amplitude usually drops off exponentially and the maximum amplitude is contained only over one or very few cycles. The level of such a pulse is generally referred to the peak-to-peak value, indicated by dB_{pp}. Some authors convert peak-to-peak values to rms values by various means and assumptions. It is often not stated how this was done, and sadly some authors don't even state whether levels are peak-to-peak or rms. However, this is only an issue for pulsed signals. Errors of a few dB might have been introduced. Furthermore, pulsed signals are often directional, and computed source levels depend on the angle of measurement, which is often unknown. This will also introduce a few dB uncertainty. Some few projects yielded source levels for directional signals as a function of measurement angle. Where listed, **DI** refers to the **directivity index** and describes the drop in amplitude as one goes from an on-axis to an off-axis receiver (see e.g. Au 1993).

2.7 Location

This column lists the geographical area where recordings of free-ranging animals were obtained. In the case of recordings made in tanks in aquaria, I simply state "captive". Where information was available as to where the animals had been captured and how long they had been captive for, I list this as well. This column is rather important for the development of automatic call detectors that will be deployed in a particular location in the wild. Different animal populations belonging to the same species, might use different calls. Animals in captivity often change their call structure and repertoire. This could be due to reverberation problems in a tank environment or due to different ambient noise, exposure, stimulation, behaviour, simply "life" in a new environment. Changes to calls will happen over time, i.e. newly captured animals might still show more features of their wild calls. Also, in a tank, emitted source levels are usually lower than in the wild. In recent years, captive environments have been made semi-natural. For example, in the Yangtze River in China, an old river arm has been closed off and houses endangered river dolphins and porpoises. This captive environment would be as close to the natural environment as it gets. Such semi-natural environments are being constructed all around the world. I have visited many of them myself. Some are mere dents in a river or small bays along the shore that have been cut off. Some are used mainly for rehabilitation, others also have a commercial component and function as an animal viewing facility. The fact is that the underwater acoustic environment is very close to the animals' natural environment (I have taken ambient noise recordings in such environments myself.). Calls recorded in such environments might be closer to calls recorded in the wild, than calls recorded in concrete tanks. However, there is still the component of changes in behaviour, exposure and stimulation affecting call emission.

3. Sounds of Porpoises

3.1 Dall's Porpoise

Type	Bandwidth Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1µPa @1m]	Location	References
clicks	5k-10k	125k-135k	0.1-1.2ms/click	120-148	not mentioned	Evans & Awbrey 1984
clicks	-	120k-160k	50µs-1ms dur./click; ICI 13-143ms; 9-40 clicks/sequ.	-	free-ranging	Awbrey *et al.* 1979 (via Hatakeyama & Soeda 1990)
echol. clicks	-	135k-149k	50-60µs dur./click; ICI 8-150ms; 9-47 clicks/sequ.	165-170	Bering Sea	Hatakeyama & Soeda 1990
echol. clicks	-	90k-115k	15-60µs dur./click; ICI 9-48ms;64-176 clicks/sequ.	154-157	captive; within 3 days of capture off Japan	Hatakeyama & Soeda 1990
clicks	12k	134k	75-109µs dur./pulse	-	Monterey Bay, CA	Kamminga *et al.* 1996

3.2 Spectacled Porpoise

The spectacled porpoise is poorly known. It is rarely seen at sea. Strandings have been reported from the southeastern coast of South America, and various offshore islands, circumpolar in the southern oceans. No records of its vocalizations were found in the literature.

3.3 Harbour Porpoise

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/ Repet.	SL [dB re 1µPa @1m]	Location	References
echol. clicks	6k-1k	2k	1.5ms dur./ click; <200 clicks/s	-	captive	Busnel *et al.* 1963 & 1965
harmonic calls	8k-100	2k	0.5-2s	-	captive from Baltic Sea, Denmark	Busnel & Dziedzic 1966
	12k-100	2k	0.25-0.7s			

clicks	20k-400	2k-4k	0.5-1.5ms dur./click; sequ. dur. <2s	125-130	captive + wild in Gulf of Maine	Schevill *et al*. 1969
echol. clicks	-	2k-4k & 110k-150k simultaneous	0.1ms dur./click	132-149	captive	Mohl & Andersen 1973
clicks	11k	120k	100µs dur.; 380 clicks/s	-	captive	Kamminga & Wiersma 1981
		sometimes simultaneous 20k				
clicks	8k	20k	201µs dur./cl.	-	captive after stranding in North Sea	Wiersma 1982
	33k	120k	36µs dur./cl.			
clicks	-	125k-140k	25-83µs dur./click; ICI 10-123ms; 4-23 clicks/sequ.	158-162	captive from Hokkaido	Hatakeyama & Soeda 1990
echol. clicks	-	107k-130k	<25 click sequences/min	150-180	semi-natural net enclosure	Akamatsu *et al*. 1994
				130-163	pool	
echol. clicks	13k @ 3dB	144k-148k	0.1ms dur.	133-166	captive; within 1yr of stranding in North Sea	Goodson *et al*. 1995; Goodson & Sturtivant 1996
echol. clicks		1.4k-2.5k	< 10ms dur./cl.	-	captive; within 1yr of stranding in North Sea	Verboom & Kastelein 1995
		distinct peaks betw. 110k-140k	0.1ms dur./click			
		13k-100k broadband	25-500 clicks/s			
		30k & 60k	< 25 clicks/s			
whistles		pure tones ranging from 47-600Hz	-	-		
clicks	21k	129k-137k	50-70µs dur./ pulse	-	captive (Washington + Denmark)	Kamminga *et al*. 1996
echol. clicks	16k	125k-130k	>100µs duration	160-165	captive	Au *et al*. 1999
echol. clicks	16k @ 3dB	131k	77µs/click	157-169pp	captive	Teilmann *et al*. 2002

Busnel and Dziedzic (1966) recorded both narrow-band clicks and pulsed calls with broadband harmonic structure from their harbour porpoises captured in the Baltic Sea, Denmark. Schevill *et al*. 1969 only detected clicks and failed to find broadband harmonic calls in the repertoire of harbour porpoises in the Gulf of Maine. They argue that Busnel & Dziedzic's recording system overloaded, that the analyzing filter did not resolve the rapid clicks and introduced higher harmonic artifacts. This is further discussed and illustrated in Verboom & Kastelein (1995). Evans (1973) as well as Mohl and Andersen (1973) believe that Schevill *et al*.'s (1969) recording system was limited in frequency bandwidth, resulting in too low-frequency energy content and missing high-frequency energy. I would like to comment that 30-40 years ago, most available equipment was limited to the audible frequency band, i.e. cut off above 20kHz. Also, hardware components were not flexible with regard to analyzing filter width in both the time and the frequency domain. It is impossible to say now whether calls recorded at those early times actually had substantial energy outside the displayed frequency range or whether spectrogram artifacts were introduced. I would suggest caution when particular calls were only described in the early articles, and have not been recorded again since.

A lot of work has been done to describe harbour porpoise sounds. The most comprehensive article is that of Verboom and Kastelein (1995). It gives a very detailed analysis of the harbour porpoise repertoire and summarizes the earlier studies. The authors found harbour porpoise clicks to occur in various patterns, such as single clicks, click trains, click bursts and click series. They found four main frequency components in their clicks (1.4-2.5kHz; distinct peaks between 110-140kHz; 13-100kHz broadband; 30kHz & 60kHz peaks). These could appear simultaneously or individually, e.g. the first component often appeared together with the second component; the fourth component only appeared when the click trains had a low pulse repetition frequency, etc. More detail on particular clicks can be found in Kastelein *et al*. (1995).

3.4 Vaquita

Type	**Bandwidth Δf [Hz]**	**Dominant f [Hz]**	**Duration/Repet.**	**SL [dB re 1µPa @1m]**	**Location**	**References**
clicks	147k-122k	128k-139k	79-193µs/click; 3-57 clicks/sequ.; ICI 19-144ms; 10-50 clicks/s	-	Gulf of California	Silber 1991

3.5 Burmeister's Porpoise

Burmeister's porpoises live along the coasts of southern South America. Not much is known about them, and no reports on their vocalizations were found in the literature.

3.6 Finless Porpoise

Type	**Bandwidth Δf [Hz]**	**Dominant f [Hz]**	**Duration/Repet.**	**SL [dB re 1μPa @1m]**	**Location**	**References**
clicks	2.2k-1.6k	2k + undetermined high-f	1.3-3.4ms dur./click; sequ.: 20-150 clicks/s	105-108	semi-natural; Indus Delta, Pakistan	Pilleri *et al.* 1980
clicks	17k	128k-130k	50-70μs dur./ click; >250 clicks/s	-	captive in tank	Kamminga *et al.* 1986
clicks	-	60k-70k	ICI 4-9μs	104-107		Zhang *et al.* 1990
echol. clicks	-	-	ICI 8-10ms	-	captive	Akamatsu *et al.* 1998
echol. clicks	-	-	ICI 38-40ms; 276ms max	-	semi-natural reserve, Yangtze River	
echol. clicks	-	125k-150k, most 140k	-	167	Yangtze River, China	Akamatsu *et al.* 2000, 2001

4. Sounds of Sperm Whales

4.1 Sperm Whales

The sperm whale is a very vocal animal that produces a variety of clicks. These sounds were first described by Worthington and Schevill (1957). Since then, the literature on sperm whale acoustic signals has grown immensely. Apart from a geographic variation in repertoire, group-specific dialects have been found in interacting groups with overlapping geographic range (Weilgart and Whitehead 1997; Rendell and Whitehead 2003).

Sperm whale clicks are now commonly categorized into four classes according to their temporal pattern. Socializing groups emit stereotyped click sequences (patterns) called "codas" over periods lasting up to several hours (e.g. Watkins 1977). Adult male sperm whales have been reported to emit three types of clicks (Mullins *et al*. 1988). "Usual" clicks are identified by an inter-click-interval (ICI) of about 0.5-1s. Clicks occurring at a much faster rate (up to 50 clicks/s) sound like and are thus called "creaks". "Slow clicks" (sometimes called "single clicks"; similar to Jaquet's "surface clicks") have very long ICIs of 3-8s.

It has been suggested that clicks serve both the communication and echolocation purposes, as well as debilitate prey. A discussion of click function is beyond the scope of this paper. Please refer to Madsen *et al*. 2002; Whitehead 2002; Fristrup and Harbison 2002; Jaquet *et al*. 2001; Weilgart and Whitehead 1988; Watkins 1977 and others.

Type	**Bandw. Δf [Hz]**	**Dominant f [Hz]**	**Duration/Repet.**	**SL [dB re 1µPa @1m]**	**Location**	**References**
usual clicks	32k-200	2k-5k	2-24ms dur./click; ICI 0.025-1.25s	-	off USA East Coast	Backus & Schevill 1966
clicks	6k-100	2k-5k	single & 5 clicks/s	173 (1/3 octave band level @ 1kHz)	Bermuda	Dunn 1969
clicks	-	2k-8k	20ms/click	166-175	Nova Scotia, Canada	Levenson 1974
click codas	20k-100	2k-6k	codas of 3-40 clicks: 0.5-1.5s dur., repeated 2-60 times over 10s-5min	-	off USA East Coast	Watkins & Schevill 1977
clicks	28k-100	2k-6k	varying betw. 1-2 clicks/s to 75 clicks/s	75-80	off USA East Coast	Watkins 1977

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	Reference s
codas			5-7 clicks per coda of 0.8-1s dur.			
clicks	30k-100	10k-16k	2-30ms/click; 1.5-3 clicks/s in sequ. <20min; single clicks every 5-10s; 60 clicks/s in 1-10s sequ.	165-180	various	Watkins 1980
slow clicks	-	-	1-3 clicks/s in sequences of 30s-5min dur.	-	Southeast Caribbean	Watkins et al. 1985
rapid clicks	-	-	<90 clicks/s in sequ. of ~30s dur.			
codas	-	-	1s dur./coda; 5 clicks/coda			
clicks	-	-	-	185 (free); 6-10dB louder in free vs. captive	various captive + free	Watkins *et al*. 1988
usual clicks	-	-	ICI 0.7-1s; train dur. 2.4s-3s	-	off Nova Scotia	Mullins *et al*. 1988
creaks	-	-	ICI <0.2s; creak dur. 27-61s	-		
slow clicks	-	-	ICI 4.6s; train dur. 32s	-		
slow clicks	16k-100	peaks betw. 1.8k-2.8k	28-124ms dur/click; high ICI 5-7s	-	Galapagos	Weilgart & Whitehead 1988
usual clicks	16k-1k	various peaks betw. 1k-10k	24ms dur/click; ICI 0.64s	-		
usual clicks	-	sequ. with ICI 0.5s	-	-	Galapagos	Whitehead & Weilgart 1990
codas	-	200-8k	0.3-1.7s coda dur.; 5 clicks/coda	-	SE Caribbean	Moore *et al*. 1993
codas	-	2k-5k	coda dur. 0.5-2.5s; 3-12 clicks/coda	-	Galapagos	Weilgart & Whitehead 1993
usual clicks	12k-100Γ; 15k-100E	2 peaks @ 400 & 2kΓ; 1.2k & 3kE	10-20ms /click; 1-2 clicks/s	-	Azores	Goold & Jones 1995

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re $1\mu Pa$ @1m]	Location	References
codas	broad-band	2k-8k	3-40 clicks/coda; <3s coda dur.	-	Caribbean & Pacific	Weilgart & Whitehead 1997; Whitehead & Weilgart 1991
various clicks	22k-100	-	2-10 clicks/s	-	Orkney Islands, Scotland	Goold 1999
slow clicks	22k-100	~5k	-	-		
rapid clicks	15k-2k	2k-4k	10-50 clicks/train of 0.5s dur.	-		
creaks	8k-2k	-	<220 clicks/s	-		
harmonic call	7k-500	1k-3k	1s dur.	-		
codas	16k-2k	6k	25-30ms/click; 456-1280ms/coda; <16 codas/series	-	Mediterranean	Pavan *et al.* 2000
clicks	betw. 3k and 12k	10k	20-30ms/click consisting of <5 pulses	<223 rms; DI ~ 30dB	Norway	Mohl *et al.* 2000
clicks	-	5k-12k;	1-2ms duration each	140	2-wk-old neonate, stranded in Texas, recorded within 1 wk of capture in rehab. tank	Ridgway & Carder 2001
		500-3k	7-20ms	148-165		
harmonic call "grunt"	4k-500	1k-2k	200ms	-		
clicks	-	-	-	185	Bismarck Sea, Papua New Gunia	Madsen *et al.* 2001
creaks	-	-	ICI decreasing within each creak from 180-20ms; <91 clicks/s	-	New Zealand	Jaquet *et al.* 2001
surface / slow clicks			ICI 5-6s; 3-8 clicks/sequ.; sequ. dur. 24s			
usual clicks	-	-	ICI 0.5-2s; 29-249 clicks/sequ.; 6-117s pause betw. sequences	-	northern Norway	Wahlberg 2002
creaks			ICI 14-400ms			

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	References
usual clicks	24k-5k @10dB power	15k	120-200μs/click; 0.7-4 clicks/s; ICI 0.25-1.4s; 5-20s pause betw. Sequences	220-236 rms	northern Norway	Madsen *et al*. 2002
creaks	23k-6k @ 10dB power	15k	100μs dur.click; <50clicks/s; creak duration 10-30s; 5-20s pause	179-205 rms		
slow clicks	5k-1k @ 10dB power	3k	0.5-10ms dur./click; either single or in sequ. with ICI 4-7s; sequ. dur. >1 min	175-190 rms		
clicks		2k-4k; 10k-15k	ICI 0.5-1.5s	DI ~ 10-30dB	Gulf of Mexico	Thode *et al*. 2002
neonate clicks	200-450 @ 10dB	300-1.7k	2-15ms dur./click	140-162 rms; low DI <8dB @ 90^o	captive; 1 from Hawaii & 1 from Texas	Madsen *et al*. 2003
harmonic grunt	-	500	50-150ms dur.	140-152		
usual clicks	25k-3k	15k	100μs dur. of main pulse on-axis	226-236 rms; 27dB DI	Norway	Mohl *et al*. 2003

Mohl *et al.* (2000) deployed a large-aperture array to record sperm whale clicks, and they found a high directionality, which had been missed in earlier studies. Mohl *et al*. (2003) further investigated highly-directional usual clicks on- and off-axis. They discuss how the angle of measurement affects the distribution of energy within the click spectrum. Furthermore, clicks appear mono-pulsed on-axis (with 40dB more energy in the main pulse than following pulses) and multi-pulsed off-axis. Computed source levels are, of course, much higher on-axis than off-axis. With the general uncertainty about the orientation of the whale at the time of recording, differences in published source levels and spectral characteristics of usual clicks can be explained.

Whitehead and Weilgart (1990) measured click rates (the number of clicks per second) in sperm whale groups. They found that the total recorded click rate depended mainly on the number of animals and their behavioural state. They deduced an average of 1.22 clicks per second per animal, which is a number that could be used to calibrate passive acoustic censuses.

With the repertoire of sperm whales rather well studied, there have been -over the past few years- various projects using passive acoustics to survey sperm whales. Most of these projects involved the development of some form of automatic detector. A discussion of these efforts is beyond the framework of the current project. For reference, the most recent peer-reviewed study is the one by Mellinger *et al*. (2004). Their article also summarizes the earlier efforts at passive acoustic sperm whale surveys.

4.2 Pygmy Sperm Whale

Type	Bandw. Δf [Hz]	Dom. f [Hz]	Duration/ Repet.	SL [dB re 1μPa @1m]	Location	References
clicks	-	< 13k	Various	-	captive; stranded	Caldwell & Caldwell 1987a
clicks	200k-60k	120k	-	-		Santoro et al. 1989
sweep	-	1.36k-1.48k swept	0.42s dur.; 18 sweeps/ 5s	-	captive; 1 day after stranding in Hawaii	Thomas *et al*. 1990
clicks	200k-60k	125k	600μs dur./ click; >20 clicks/s	-	captive; stranded in Monterey Bay	Marten 2000
clicks	20k @3dB	130k	120μs	-	Stranded in New Jersey; recordings taken in rehab. tank	Ridgway & Carder 2001

Caldwell *et al*. (1966) recorded calls from a pygmy sperm whale with a contact microphone in air, while the animal was out of the water. Ridgway and Carder (2001) discuss the limitations of Caldwell *et al*.'s equipment and procedure, yielding unrealistically low-frequency calls.

4.3 Dwarf Sperm Whale

The dwarf sperm whale is an inconspicuous animal that is rarely seen at sea. Reported sightings come from all the major coasts along the Pacific, Atlantic and Indian Oceans. However, no records of its acoustic signals were found in the literature.

5. Sounds of Beaked Whales

Beaked whales are the least known of all cetaceans. They generally live in deep water far from our coasts. How rare they are is controversial. They are rarely encountered at sea, making censusing very difficult. Most information about beaked whales comes from stranded animals or dead animals washed ashore. In fact, some of the species have never been seen alive. Given the rarity of encounters, it is not surprising that so little is known about their acoustic repertoire. On the other hand, their 'rarity' does not mean that acoustic impact on beaked whales is negligible. Indeed, they appear rather susceptible to noise-induced auditory damage as indicated by recent strandings around underwater noise emissions.

5.1 Baird's Beaked Whale

Type	Bandwidth Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	References
harmonic FM whistles	>20k-4k	4k-8k	3s dur.	-	Oregon	Dawson & Ljungblad 1998
single clicks or slow click sequ.	minor peaks betw. 130k-12k	22k-25k	122-953μs/click; ICI 100-540ms; 22-2520ms dur./sequ.	-		
fast click sequ.	minor peaks <134k	23k & 42k	122-549μs/click; ICI 7ms; 33-580ms/sequ.	-		
click bursts	<90k	23k-25k	44ms dur/burst	-		

5.2 Arnoux's Beaked Whale

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	References
AM call	8.5k-1k	3.9k-5.6k	0.8s dur.	-	Kemp Land, Antarctica	Rogers & Brown 1999
slow clicks	18k-14k	16k	-	-		
click trains	20k-3k	12k-20k	25 clicks/train; 1.2s dur./train; 34 clicks/s	-		
click bursts	-	3k-11k	0.5s dur/burst			
whistles	-	4.3k-5.2k	0.65s dur.	-		

5.3 Northern Bottlenose Whale

Type	Bandwidth Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	References
whistles	-	3k-16k	0.1-0.9s dur.	-	Nova Scotia, Canada	Winn *et al.* 1970[1]
clicks	>26k-500	-	-	-		
surface clicks	2k @ 3dB	peaks betw. 4k-22k	2ms dur./click; ICI 0.7s; 20s dur/sequ.	-	Nova Scotia, Canada	Hooker & Whitehead 2002
deep-water clicks	4k @ 3dB	21k-25k	0.4ms dur/click; ICI 0.4s	-		

5.4 Southern Bottlenose Whale

Although this animal has been observed at sea, no recordings of its sounds have been found in the literature.

5.5 Cuvier's Beaked Whale

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration/Repet.	SL [dB re 1μPa @1m]	Location	References
Clicks	17k-13k	ranging from 13k-16k	0.7-1.6ms dur./click; ICI 0.4-0.5s; 35-105 clicks/sequ.; 16-45s dur./sequ.	-	Mediterranean	Frantzis *et al.* 2002

This seems to be the most wide-spread animal, occurring in all the world's large oceans.

5.6 Shepherd's Beaked Whale

There have been some very few possible sightings around Australia and South America, without acoustic recordings.

[1] I was unable to obtain a copy of Winn *et al.* 1970. The data listed in the table were taken from various citations of Winn *et al.*'s study.

5.7 Blainville's Beaked Whale

Type	Bandw. Δf [Hz]	Dominant f [Hz]	Duration	SL [dB re 1μPa @1m]	Location	References
whistles/ rapid narrowband pulses	1k	<1k – 6k	0.2-1s dur./call	-	beached in Florida (recordings made in air)	Caldwell & Caldwell 1971

5.8 Sowerby's Beaked Whale

This is one of the most commonly stranded *Mesoplodon* species, however, it has only rarely been encountered at sea. No reports of its vocalizations were found.

5.9 Gervais' Beaked Whale

Clicks of variable repetition rate have been heard from stranded animals in Florida (Caldwell and Caldwell 1987b).

5.10 True's Beaked Whale

Only 'possible' sightings at sea have been reported for this animal. There is no data on its vocalizations.

5.11 Strap-toothed Beaked Whale

Relatively often seen in the southern oceans but without corresponding acoustic observations.

5.12 Gray's Beaked Whale

There have been relatively many sightings of this animal in the southern oceans, however no accords of its vocalizations.

5.13 Andrew's Beaked Whale

This animal has not been seen at sea according to Cawardine (1995), but about two dozen individuals have been found stranded.

5.14 Longman's Beaked Whale

Longman's Beaked Whale is probably the least known of the world's whales, since research is based on only two weathered skulls (Carwardine 1995).

5.15 Hector's Beaked Whale

There are only 'possible' reports of identification of Hector's Beaked Whale at sea. Strandings have occurred in the southern oceans and off the North American west coast.

A free-swimming *Mesoplodon* (probably *hectori*) produced ultrasonic clicks (Ljungblad, unpublished data, via Dawson and Ljungblad 1998).

5.16 Ginkgo-toothed Beaked Whale

This animal has been observed around the Pacific Ocean, including a few strandings, however, no reports of its acoustic signals have been found.

5.17 Stejneger's Beaked Whale

These animals have been sighted in the North Pacific, however, no studies of their acoustic repertoire have been attempted.

5.18 Hubbs' Beaked Whale

Type	**Bandwidth Δf [Hz]**	**Dominant f [Hz]**	**Duration/Repet.**	**SL**	**Location**	**References**
Clicks	2k-300	1k-2k	7 clicks/sequ.; 80 clicks/s; 90ms dur/sequ.; 142ms betw. sequences	-	stranded in California, captive recordings	Buerki *et al*. 1989; Lynn & Reiss 1992
	>40k-300	10k-30k				
whistles	-	2.6k-10.7k	156-450ms dur.	-		
clicks	-	1.77k	3-8 clicks in sequ. of 24-307ms dur.; ICI 4-36ms	-		Marten 2000
	-	>78k-10k		-		

All recordings reported for Hubbs' Beaked Whales were obtained from the same two males. These were very young, possibly neonate animals. As stranded animals often suffer from respiratory infections that could affect sound production, healthy animals in the wild (and older animals) might produce different sounds.

5.19 Pygmy Beaked Whale

Few strandings and potential sightings off Peru have been reported. Nothing is known about its acoustic emissions.

6. Summary and Conclusion

The purpose of this project was to describe the acoustic repertoire of selected odontocete species. This data can be used to construct automatic acoustic detectors and classifiers for odontocetes. Passive acoustic detectors find their application in marine mammal censusing, or as a first step in underwater noise mitigation, where the presence/absence of animals needs to be known before anthropogenic (man-made) noise can be emitted.

If some anthropogenic activity is proposed in a specific area, one would first need to find out which marine mammal species frequent this area. General maps of marine mammal habitat can be found in various locations, e.g. the Eyewitness Handbook "Whales, Dolphins and Porpoises – The visual guide to all the world's cetaceans" by Mark Carwardine (Dorling Kindersley 1995) illustrates each species' general habitat. The Smithsonian Institution keeps a webpage with marine mammal information and habitat ranges (http://www.nmnh.si.edu/msw/). There are currently collaborative efforts underway in the United States to document and make publicly available marine mammal distribution charts world-wide. These will incorporate seasonal habitat changes. Alternatively, a marine mammal census could be carried out in the area of proposed underwater activity. Once it is known which species are likely to be encountered, the sound recorded from these animals in this area can be looked up in the current report. The references of the report point to which institutions and scientists have actual recordings, which would be useful for the development of robust automatic detectors. As a next step, one would then have to gather ambient noise recordings for the same location. Underwater noise of both natural and anthropogenic origin needs be investigated carefully. I would feel confident that an automatic detector could be designed for all of the whale calls listed in this paper. The more difficult part is to reduce the false alarm rate. As an example, if the target animal emits broadband clicks in series, then the detector must not be triggered by a distant ship emitting pulsed and broadband propeller cavitation noise. It is the overlap of features in the call with certain types of ambient noise that leads to false alarms. During the optimization of an automatic call detector, noise must basically also be 'recognized' and classified as such.

What type of detector and classifier would be best depends on the type of calls to be detected, the variation between different types of calls, the reproducibility of calls, as well as the characteristics of ambient noise at the location of interest. The engineering literature on signal detection in noise is immense. There is a multitude of methods to choose from. The literature on the detection of bioacoustic signals in noise has been growing over the past few years. Methods can be applied in different domains, e.g. in the time-versus-pressure representation of signal and noise, in the frequency domain by employing band-pass filters, or in the spectrogram domain, after wavelet transform, or after other transformations and feature extractions from signal and noise. An example where some methods were applied to the detection of odontocete calls in ship noise can be found in Erbe *et al*. 1999. Nowadays, every passive acoustic census of marine mammals involves some form of automatic detection, be it on a simple or rather intricate level. A review of automated passive acoustic detection methods for marine mammal calls would be a recommended start before particular detectors are designed for particular species and environments.

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